The Great Rift and the Evolution of the Craters of the Moon Lava Field, Idaho

by

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ABSTRACT

The Snake River Plain of southern Idaho is a region of late Cenozoic and Quaternary basalt volcanism and many volcanic rift zones. The most spectacular volcanic rift zone on the plain is the Great Rift, an 85-kilometer-long and 2- to 8-kilometer-wide belt of cinder cones, shield volcanoes, eruptive fissures, and open cracks. The Holocene and latest Pleistocene Craters of the Moon lava field is alined along a 45-kilometer segment of the northern part of the Great Rift. The lava field is a composite of more than forty lava flows that have erupted from more than twenty-five vents. It covers an area of about 1,650 square kilometers, contains about 30 cubic kilometers of lava, and is the largest dominantly Holocene basalt lava field in the conterminous United States. Radiocarbon and paleomagnetic data reveal that lava flows of the Craters of the Moon lava field were emplaced in at least eight eruptive periods that began about 15,000 years ago and ended about 2,000 years ago. The lava flows of the Craters of the Moon field were erupted from cinder cones and fissures, most of which are in the Craters of the Moon National Monument. Two other Holocene lava fields on the Great Rift, the Kings Bowl and Wapi fields, represent a small-volume (about 0.005 cubic kilometer) fissure eruption and a large-volume (about 6 cubic kilometers) shield eruption, respectively.

INTRODUCTION

The Snake River Plain of southern Idaho is a region of geologically young basalt volcanism. As many as eight lava fields in the area are known or believed to be younger than 20,000 years old: they include the Craters of the Moon, Kings Bowl, Wapi, Hells Half Acre, Cerro Grande, North Robbers, South Robbers, and Shoshone lava fields (Figure 1).

The Craters of the Moon, Wapi, and Kings Bowl lava fields lie along the Great Rift, an 85-kilometer-long and 2- to 8-kilometer-wide belt of shield volcanoes, cinder cones, eruptive fissures, associated lava flows, and noneruptive fissures. In this report, we describe the largest of these lava fields—the Craters of the Moon field. This lava field, the largest accumulation of dominantly Holocene lava in the conterminous United States, covers an area of 1,650 square kilometers and contains approximately 30 cubic kilometers of lava. The Wapi and Kings Bowl lava fields to the southeast have been described and mapped by Kuntz and others (1980, 1981), King (1977), Covington (1977), Champion (1973), and Champion and Greeley (1977); they are described in only minor detail in this report.

REGIONAL SETTING

The Snake River Plain is an arcuate topographic depression, 50 to 100 kilometers wide, that extends from near Payette, Idaho, on the west for about 250 kilometers southeastward to Twin Falls and then for about 300 kilometers northeastward to near Ashton, Idaho (Figure 1). It is bounded on the north by Mesozoic and early Tertiary granitic rocks of the Idaho batholith and by Tertiary and Quaternary basin-range, block-faulted mountains. The southeast side of the plain is also bounded by basin-range, block-faulted mountains. The southwest side of the plain is bounded by Tertiary rhyolitic and basaltic rocks of the Owyhee Plateau. Upper Tertiary and Quaternary rhyolitic and basaltic rocks of the Yellowstone Plateau occur at the northeast end of the plain. Geologists and geophysicists have traditionally divided the Snake River Plain into eastern, central, and western parts based on different geological histories

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and geophysical features in each part (Mabey, 1976, 1978, and 1982 this volume).

GENERAL FEATURES OF THE CENTRAL AND EASTERN SNAKE RIVER PLAIN

The central and eastern Snake River Plain is a broad, flat lava plain consisting, at the surface, of basalt lava flows and thin, discontinuous, interbedded loess, eolian sand, and alluvial fan deposits that together have a total thickness of about 1 to 2 kilometers near the area described in this report (Zohdy and Stanley, 1973; Stanley and others, 1977; Doherty and others, 1979). Lava flows of the central and eastern Snake River Plain were erupted from low volcanic vents that are generally alined with and parallel to volcanic rift zones that trend mainly at right angles to the long axis of the eastern Snake River Plain. We define a volcanic rift zone as a narrow belt of faults, grabens, noneruptive fissures, eruptive fissures, spatter cones, spatter ramparts, cinder cones, lava cones, pit craters, and shield volcanoes. Most eruptive vents in volcanic rift zones are elongated and are believed to overlie eruptive fissures (Wentworth and Macdonald, 1953; Kuntz, 1977a, 1977b). Well-defined volcanic rift zones of the Snake River Plain are as much as 10 kilometers wide and 120 kilometers long. The Great Rift is the best example of a volcanic rift zone in the Snake River Plain.

In the central and eastern Snake River Plain, the basaltic volcanism represents the latest phase of a complex and poorly understood tectonic and volcanic history that also includes an earlier phase of rhyolitic volcanism. Available geological, geophysical, radiometric, and drilling data suggest that the rhyolitic

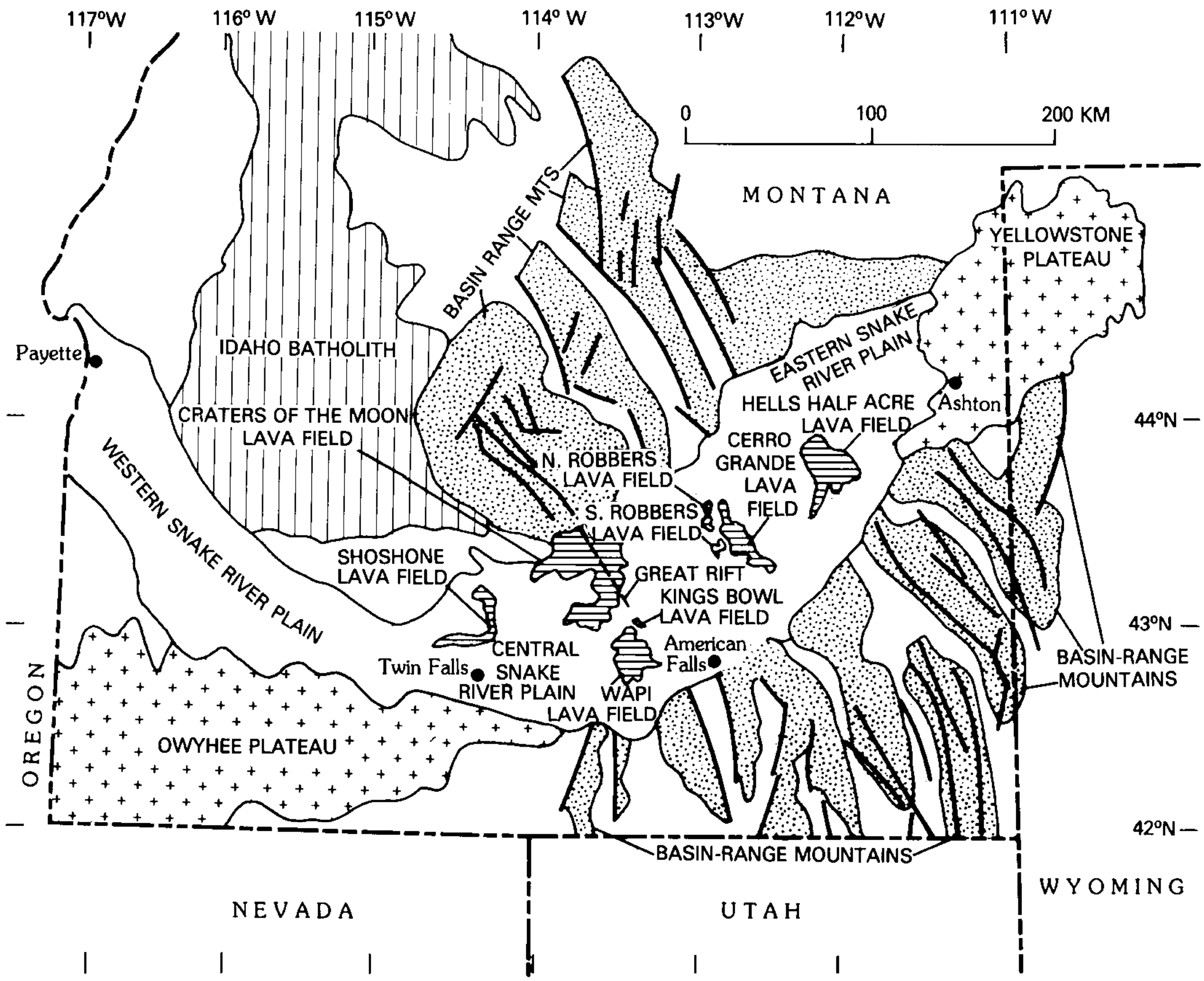

Figure 1. Generalized map of southern Idaho showing major geologic and physiographic features and locations referred to in the text.

rocks were erupted from rhyolitic calderas alined in a northeast-trending belt. The earliest calderas are believed to have formed originally about 12 to 15 million years ago near Twin Falls and to have become progressively younger northeastward to Yellowstone National Park. Models describing the formation of the belt of calderas are discussed by Armstrong and others (1975), Eaton and others (1975), Christiansen and McKee (1978), Mabey and others (1978), and Leeman (1982 this volume).

BASALTIC VOLCANISM IN THE CENTRAL AND EASTERN SNAKE RIVER PLAIN

Basaltic volcanism has occurred as fissure eruptions within volcanic rift zones in many parts of the world, including Hawaii (Macdonald and Abbott, 1970), Iceland (Macdonald, 1972), and the eastern Snake River Plain (Kuntz, 1977a, 1977b), especially along the Great Rift. Based on well-documented Hawaiian eruptions, we believe that typical eruptions along the Great Rift consisted of distinct, though gradational, stages. The stages described below represent a generalized gradational sequence during a prolonged basaltic eruption cycle; individual eruptions along the Great Rift may have included only some of the phases described. Distinctive volcanic landforms representative of each phase of such an eruptive cycle are found along the Great Rift.

Eruptions generally began with a long line of lava fountains that extended for hundreds of meters and locally for a few kilometers along a single fissure or a series of en echelon fissures. Voluminous outwelling of fluid lava along nearly the entire fissure accompanied fountaining. The basaltic lava in the early eruptive stages was extremely fluid and heavily charged with dissolved gases. The early stages of such eruptions led to the development of spatter ramparts and downwind blankets of fine-grained tephra.

After several hours or days, the eruption generally diminished and lava fountains became localized along short segments of fissures. Spatter ramparts were succeeded by spatter or cinder cones which built up around the lava fountains.

After several hours, days, or weeks, a decrease in magma pressure and in the amount of dissolved gas in the magma produced a corresponding decrease in the height of lava fountains and thus to a change in the types of volcanic processes and landforms. During historic, long-lived Hawaiian activity and, by inference, during prehistoric volcanic activity along the Great Rift, fountaining diminished and was followed by quiet but voluminous outpourings of lava over or through the existing spatter or cinder cones. A prolonged period of overflow of lava in most places produced a lava cone composed largely of sheets of pahoehoe lava that mantled the older cone structure. Lava-cone summits are typically indented by an elongated crater. The elongation of the crater is generally parallel to the underlying fissure or rift, which served as the channelway for magma to the vent. Large craters were formed by collapse of the crater walls, accompanied by repeated crater filling and draining.

Where eruption of fluid basaltic lava extended over periods of months and possibly years at a single vent, large lava cones or shield volcanoes were produced. These broad, low, rounded, shield-shaped landforms grew by the continued buildup of thin, far-spreading pahoehoe and, to a lesser extent, áa lava flows. Little explosive activity was involved in the shield-building stage.

PREVIOUS WORK AND METHODS OF THE PRESENT STUDY

This report summarizes various field and laboratory studies that we have carried out over the last ten years. Our studies of the Craters of the Moon lava field were prompted by the U. S. Geological Survey's regional study of the basalt volcanism of the eastern Snake River Plain and by the Survey's study and evaluation of the geology and mineral resources potential of the Great Rift Wilderness Area, a proposed U. S. Bureau of Land Management wilderness area that includes most of the Craters of the Moon and Wapi lava fields (Kuntz and others, 1980, 1981).

The Craters of the Moon lava field has been studied in more detail than any other lava field in the Snake River Plain. Reports by Russell (1902), Stearns (1928), Murtaugh (1961), and Prinz (1970) outlined the basic geologic framework of the lava field. Lefebvre (1975) identified four major groups of lava flows or eruptive pulses in the evolution of the Craters of the Moon lava field by analyzing Landsat images. Champion and Greeley (1977) conducted preliminary studies on the paleomagnetic properties of the Craters of the Moon lava flows and found that paleomagnetic methods could be used for relative dating of individual flows and for correlation of flows that are separated from one another but are believed to be coeval on the bases of field characteristics and stratigraphic relations. Our combined field studies in the summers of 1978 and 1979 made use of Lefebvre's gross stratigraphic relations for major eruptive units, Champion's paleomagnetic data, and preliminary photogeologic maps of the Craters of the Moon lava field compiled at a scale of 1:24,000. We mapped the entire lava field and collected samples for radiocarbon, paleomagnetic, and petrographic studies and for chemical analyses. Maps of the Craters of the Moon, Wapi, and Kings Bowl lava fields and of structures along the Great Rift, all at a scale of 1:125,000, were published by Kuntz and others (1980, 1981).

The suspected youthfulness of the lava flows erupted along the Great Rift was confirmed by the first published radiocarbon ages of charcoal obtained from beneath lava flows of the Kings Bowl lava field and from tree molds in some of the youngest lava flows in the Craters of the Moon lava field. Prinz (1970) reported an age of 2,130 ± 60 years b.p. for the Kings Bowl lava field, and Bullard and Rylander (1970) and Valastro and others (1972) reported ages of about 2,100 years b.p. for some of the youngest flows in the Craters of the Moon lava field.

We have determined thirty-five additional radiocarbon ages for flows in the Craters of the Moon lava field from organic soil and charcoal samples. The soil and some of the charcoal samples were obtained by excavating beneath the lava flows with a backhoe. The radiocarbon dating study has yielded ages of variable accuracy that require further analysis and interpretation, but the relative ages of major groups of flows for the Craters of the Moon lava field were determined with reasonable accuracy (Table 1). The informal names and the stratigraphic order of the lava flows in each group of flows and approximate ages of the groups of flows are also given in Table 1.

Paleomagnetic measurements on samples from the lava flows of the Craters of the Moon lava field have been used to correlate lava flows, to obtain rough age designations for individual flows and groups of flows, and thereby to decipher the volcanic history of the lava field (D. E. Champion, unpublished data). Each lava flow in the lava field has preserved a record of the local geomagnetic field at the time of its cooling. With the knowledge that secular variation of the geomagnetic field occurs at a geologically rapid rate (4 degrees per century, Champion and Shoemaker, 1977), comparisons of paleomagnetic directions have permitted assignment of lava flows to groups of similar paleomagnetic direction. Conversely, dissimilar paleomagnetic directions are strong evidence that two lava flows do not belong to the same group.

THE GREAT RIFT AND ASSOCIATED VOLCANIC DEPOSITS

The Great Rift (Stearns, 1928; Prinz, 1970) consists of volcanic vents, eruptive fissures, and noneruptive fissures that extend approximately 85 kilometers from the southern Pioneer Mountains southeastward through Craters of the Moon National Monument to Pillar Butte in the Wapi lava field, located about 30 kilometers northwest of American Falls (see Figures 1, 2, and 3A). Three Holocene and latest Pleistocene lava fields—the Craters of the Moon, Wapi, and Kings Bowl—are alined along the trend of the Great Rift. The Kings Bowl lava field is made up of lava flows that originated during a single volcanic episode from fissures on the southern part of the Great Rift. The Wapi lava field is a broad shield volcano with a main vent complex at Pillar Butte on the southern part of the Great Rift. Paleomagnetic (Champion and Greeley, 1977) and radiocarbon studies show that the lava flows of the Wapi lava field and the Kings Bowl lava field were erupted simultaneously about 2,250 years ago over a period of a few tens of years and possibly as short as several weeks or months.

Cinder cones and eruptive fissures occur along the 45-kilometer-long, N. 35° W.-trending Craters of the Moon segment of the northern part of the Great Rift, but they are especially abundant within the Craters of the Moon National Monument. At the southeastern limit of the Craters of the Moon lava field, the Great Rift emerges from beneath lava flows as four sets of open cracks that trend N. 27° W. to N. 43° W., and from which no lava has erupted. Farther south, the Kings Bowl lava field formed along an 11-kilometer-long, N. 15° W.-trending segment of open cracks and eruptive fissures in the Great Rift. The lava flows of the Wapi lava field were erupted from at least five craters that form the vent complex at Pillar Butte. The elongated vents at Pillar Butte are alined in a N. 20° W. direction and suggest that a segment of the Great Rift is buried beneath the Wapi lava field.

Many volcanic rift zones in the central and eastern Snake River Plain appear to be extensions onto the plain of northwest-trending range-front faults that bound basin-range block-fault mountains along the margins of the plain (Kuntz, 1977a, 1977b). In contrast, the Great Rift does not lie on an extension of a range-front fault, but it may be a southeastward extension of a basement structure in older rocks that extends northwest from the margin of the plain. A magnetic high and gravity low centered in the area of Craters of the Moon National Monument probably reflects a deep-seated intrusive body (Kuntz and others, 1980). The magnetic anomaly extends northwestward and is continuous with a northwest-trending magnetic high over a zone of Tertiary intrusive rocks that extends for about 90 kilometers northwest of the plain. The Great Rift and the zone of Tertiary intrusive bodies probably are the expression in the upper crust of a northwest-trending basement structure that extends across nearly the entire width of the

Table 1. Eruptive periods, approximate age of eruptive periods, informal names of lava flows of the upper part of the Snake River Group, and source vents for lava flows in the Craters of the Moon, Wapi, and Kings Bowl lava fields.

Eruptive period and approximate age	Informal name and lava type of major flows* (in order of ascending stratigraphic position)	Source vents (queried where uncertain)
A 2,100 to 2,300 years b.p.	Broken Top (p)	Broken Top, east and south sides
	Blue Dragon (p)	Eruptive fissures south of Big Craters cinder cone
	Trench Mortar Flat (p)	Eruptive fissures between Big Cinder Butte and The Watchman cinder cone
	North Crater (p)	North Crater cinder cone
	Big Craters (Green Dragon) (p)	Eruptive fissure at north end of Big Craters cinder cone
	Kings Bowl (p)	Fissure vents north and south of Kings Bowl
	Wapi (p)	Vents at Pillar Butte
	Serrate (a-b)	North Crater(?)
	Devils Orchard (a-b)	North Crater cinder cone(?)
	Highway (a-b)	North Crater cinder cone(?) or tholoid vent
B 3,500 to 4,500 years b.p.	Vermillion Chasm (p)	Eruptive fissures at Vermillion Chasm
	Deadhorse (p)	Eruptive fissures north and south of Black Top Butte cinder cone
	Devils Cauldron (p)	Devils Cauldron
	Minidoka (p)	Obscure vents located about 5 kilometers northeast of New Butte cinder cone
	Larkspur Park (p)	
	Rangefire (p)	Black Top Butte cinder cone(?)
C 5,800 to 6,200 years b.p.	Indian Wells north (a)	Big Cinder Butte cinder cone(?)
	Indian Wells south (a)	Big Cinder Butte cinder cone(?)
	Sawtooth (a)	Big Cinder Butte cinder cone
	South Echo (p)	Eruptive fissures south of Echo Butte cinder cone
	Sheep Trail Butte (p-a)	Sheep Trail Butte cinder cone
	Fissure Butte (p-a)	Fissure Butte cinder cone
	Sentinel west (p)	The Sentinel cinder cone
	Sentinel south (p)	The Sentinel cinder cone
D About 6,600 years b.p.	Silent Cone (a)	Silent Cone cinder cone
	Carey Kipuka (a)	Silent Cone cinder cone(?)
	Little Park (a)	Silent Cone cinder cone(?)
	Little Laidlaw Park (a)	Silent Cone cinder cone(?)
E 7,300 to 7,800 years b.p.	Grassy Cone (p)	Grassy Cone cinder cone
	Laidlaw Lake (p)	Grassy Cone cinder cone
	Lava Point (a)	Great Rift northwest of Echo Crater
F 10,000 to 11,000 years b.p.	Pronghorn (p)	Great Rift near Sheep Trail Butte
	Bottleneck Lake (p)	Great Rift near Sheep Trail Butte
	Heifer Reservoir (p)	Great Rift near Crescent Butte
G 12,000 to 12,900 years b.p.	Sunset (p)	Sunset Cone cinder cone
	Carey (p)	Sunset Cone cinder cone
	Lava Creek (p-a)	Vents near Lava Creek
H About 15,000 years b.p.	Kimama (p)	unknown
	Bear Den Lake (p)	unknown
	Baseline (p)	unknown
	Little Prairie (p)	unknown Echo Crater and (or) Crescent Butte(?)
	Lost Kipuka (p)	unknown
	No Name (p)	unknown
	Brown flow (p)	unknown

*(p) chiefly pahoehoe flows
(a) chiefly áa flows
(a-b) áa and block flows
(p-a) pahoehoe and áa flows

central and eastern Snake River Plain and into the region to the northwest.

CRATERS OF THE MOON LAVA FIELD

The Craters of the Moon lava field is a composite of more than forty lava flows erupted from more than twenty-five cinder cones and eruptive fissures, most of which are in Craters of the Moon National Monument (Figure 2). The lava field formed during at least eight periods of eruptive activity, each of which was about 1,000 years or less duration and separated by intervals of quiescence lasting from a few hundred years to more than two thousand years. The sequential development of the Craters of the Moon lava field during its eight periods of eruptive activity is shown in Figure 3.

LAVA FLOWS

Most flows of the lava field are pahoehoe; they have hummocky, billowy, ropy, and wrinkled surfaces that reflect the fluid nature of the lava. The upper centimeter of many fresh, unweathered flows consists of vesicular to dense glass that has a striking blue to green irridescence. The pahoehoe flows were typically fed through lava tubes and tube systems. Localized collapse of the roofs of the lava tubes in the Broken Top and Blue Dragon flows (Figure 3A) formed "skylights" and entrances to lava tunnels that are popular attractions to visitors in Craters of the Moon National Monument. Pressure ridges and pressure plateaus are common large-scale features of the surfaces of the pahoehoe flows.

Some flows are of áa lava that has a rough, jagged, clinkery surface. Large areas of the surface of áa flows consist of irregular blocks of broken lava, some of which are broken slabs of pahoehoe. The inner parts of the áa flows are typically massive. Many surfaces of áa flows in the Craters of the Moon lava field are littered with blocks and monoliths of well-bedded cinder and spatter material as much as hundreds of meters across, which were broken from cinder cones at the source vent; notable examples are the Serrate, Sawtooth, and Silent Cone áa flows (Figures 2 and 3A). A few flows such as the Highway flow (Figures 2 and 3A) consist of block lava that is characterized by irregular blocks of dense, glassy lava with smooth surfaces. The lava flows (informal units in the upper part of the Snake River Group), cinder cones, and eruptive fissures of the Craters of the Moon, Wapi, and Kings Bowl lava fields lie on older lava flows of the Snake River Group. The younger lava flows (Holocene and latest Pleistocene informal units of the Snake River Group) in the Craters of the Moon lava field have fresh, nearly unweathered, glassy (typically blue) crusts, and they are not covered by eolian deposits. The older (Pleistocene) lavas are generally covered by a variable thickness of eolian deposits, and exposed parts of the flows are light colored, less dense, weathered, and weakly to strongly oxidized.

ERUPTIVE FISSURES

Eruptive fissures are strikingly displayed in the Craters of the Moon National Monument, particularly in the Trench Mortar Flat area between Big Cinder Butte and The Watchman cinder cones (Figure 2). During early parts of eruptions along these fissures, fountains of lava, commonly called "curtains of fire," erupted on fissure segments as long as several kilometers. The fountains built spatter ramparts and low walls of agglutinated spatter along the margins of the fissures. Copious volumes of lava flowed away from the fissures to form extensive flows. After the curtain-of-fire phase of a fissure eruption, lava typically erupted from one or two places along the fissures and formed low spatter and cinder cones.

CINDER CONES

Cinder cones are widely scattered throughout the eastern Snake River Plain but they are best developed in size, shape, and number along the Great Rift, mainly within the Craters of the Moon National Monument (Figure 2). More than twenty-five cones occur in a zone about 28 kilometers long and as much as 2.5 kilometers wide. The cinder cones are composed of agglutinated and nonagglutinated tephra layers interbedded with thin lava flows. In the Monument area, prevailing winds from the west and southwest caused greater downwind accumulation of tephra on the east or northeast sides of many cinder cones. Particularly good examples of asymmetric cinder cones are Paisley Cone and Inferno Cone (Figure 2). Composite cinder cones such as Sunset Cone and Big Craters (Figure 2) formed by overlapping accumulations of ejecta from several contemporaneous or nearly contemporaneous lava fountains. The composite cones contain many pits and have elongate crater walls alined along the eruptive fissure. Many of the cinder cones are breached on the northwest or southeast flanks or both. The breaches probably formed by a number of mechanisms: (1) by the burrowing of lava flows erupted along a feeder fissure

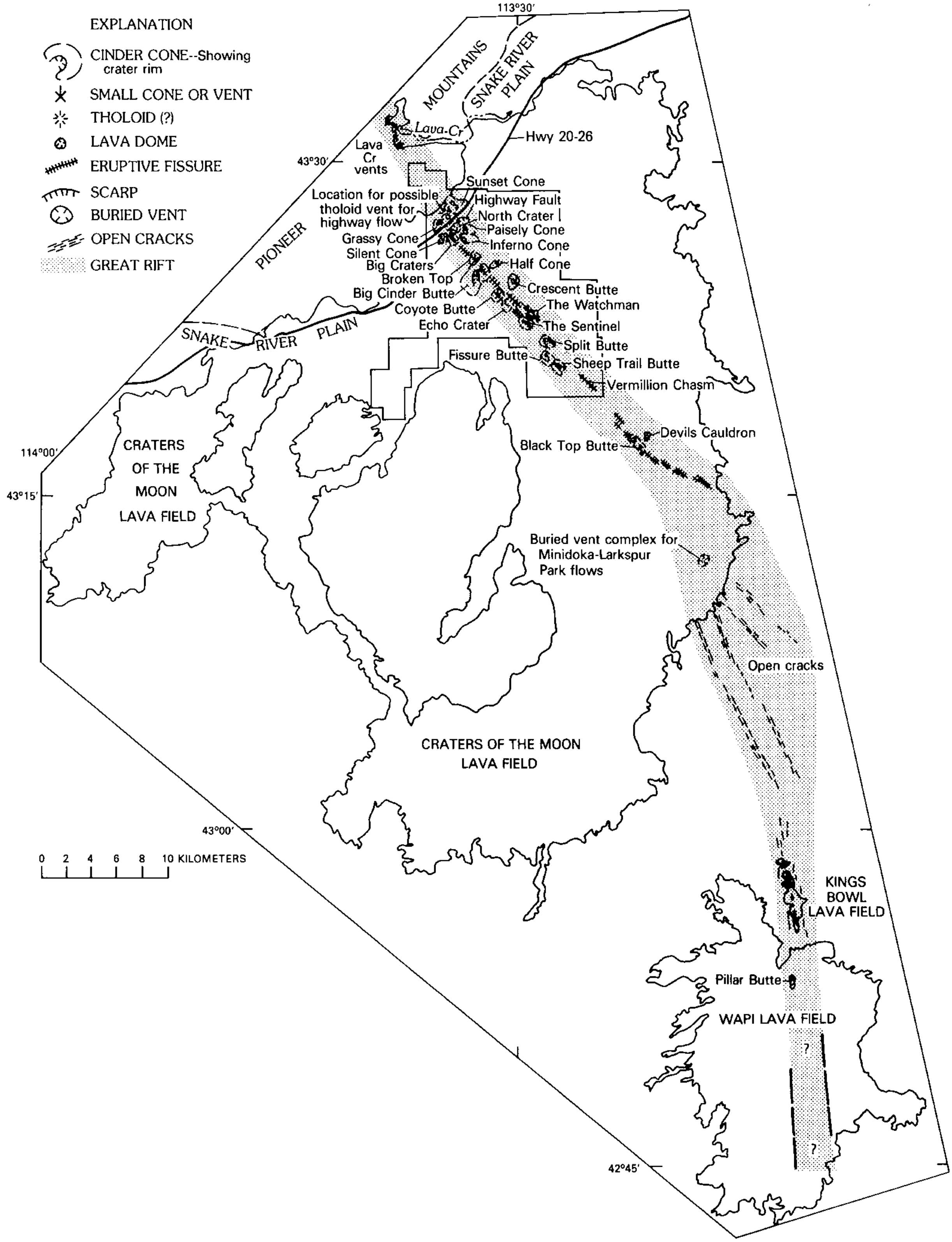

Figure 2. Map of the Great Rift showing geographic, volcanic, and structural features.

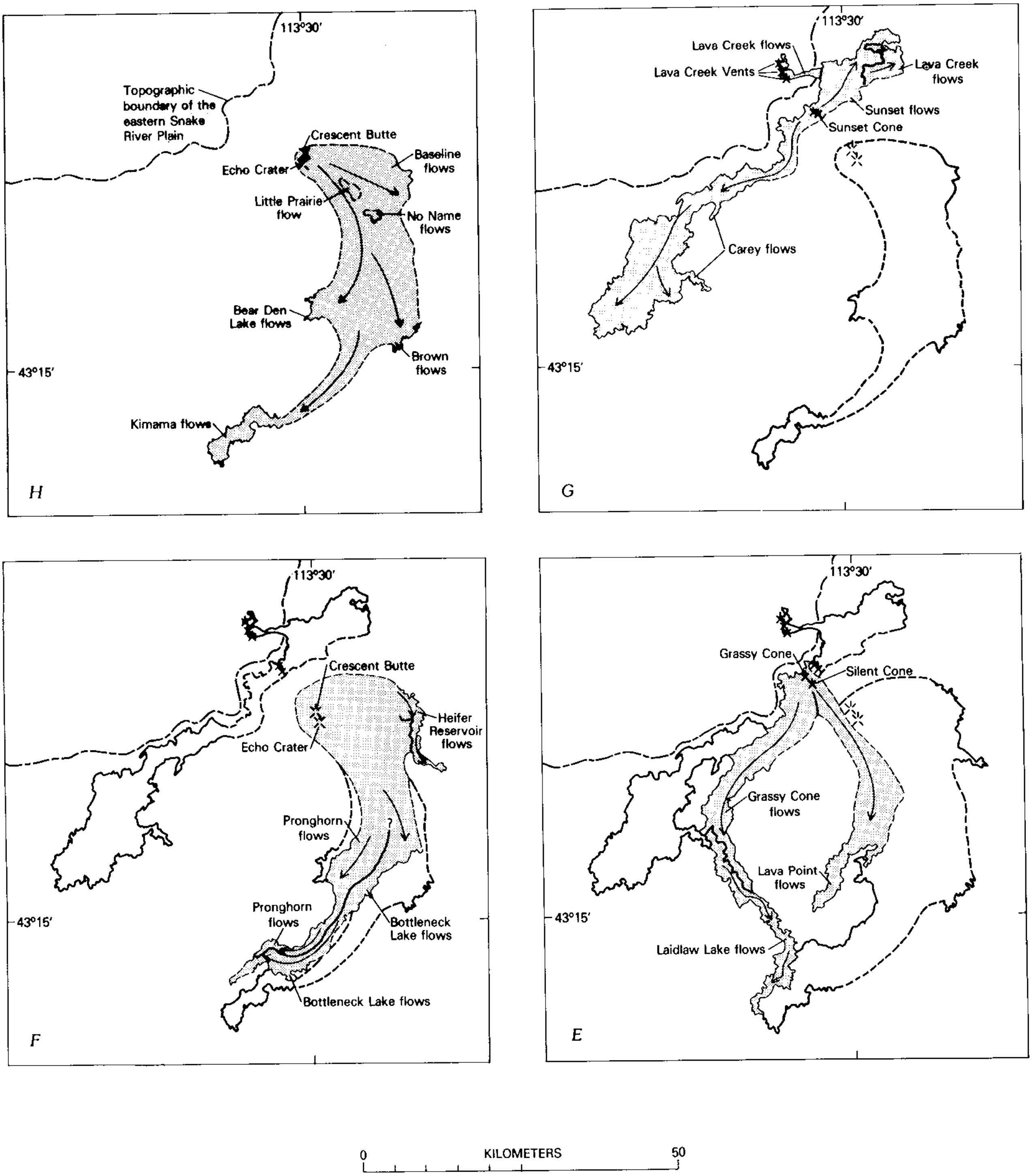

Figure 3. Diagram showing the sequential development of the Craters of the Moon lava field from the oldest eruptive period (H) to the youngest eruptive period (A).

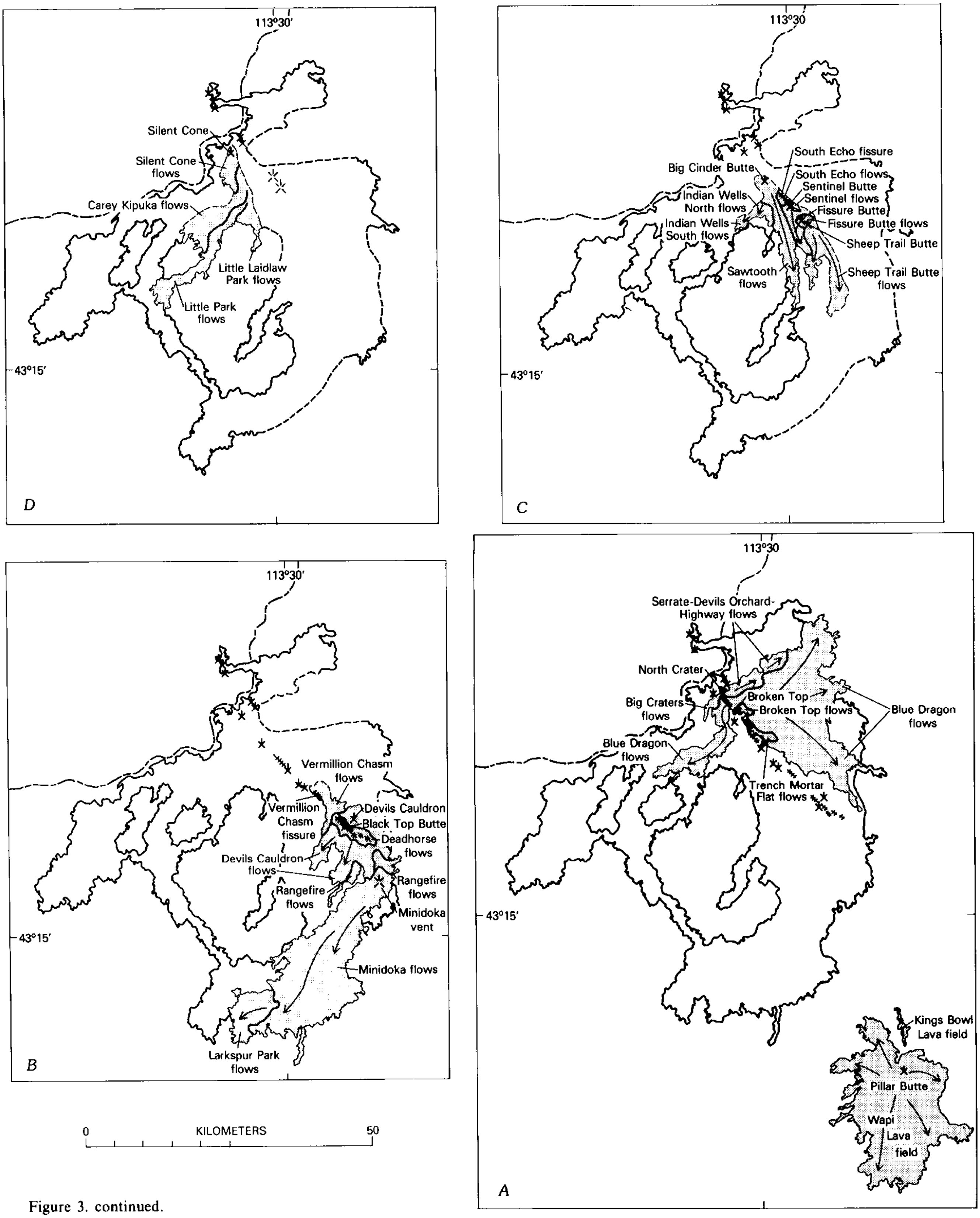

Figure 3. continued.

beneath the cones after they formed, (2) by the burrowing of lava flows through, and erosion of, the walls of the cinder cone, (3) or by the removal of ejecta by a lava stream that flowed from the feeder fissure during formation of the cones. Some cinder cones appear to have had a multistage history. Younger lava erupted from vents in North Crater, The Watchman, and Sheep Trail Butte cinder cones (Figure 2) as volcanic activity in and near them was rejuvenated.

VOLCANIC HISTORY

Lava flows and groups of flows that are believed to have similar ages, based on field, radiometric, and paleomagnetic data, can be grouped into what we term "eruptive periods." Eight eruptive periods (A through H) are presently recognized in the Craters of the Moon lava field. Because we have sampled only some of the flows from each eruptive period and because our radiocarbon studies have yielded only minimum ages, the ages of the beginning and end, and thus the durations of each eruptive period are uncertain. Paleomagnetic studies show, however, that the durations of most of the younger eruptive periods were probably less than a few hundred years. The intervals between eruptive periods may have been times of volcanic quiescence or sporadic volcanic activity, and the times within eruptive periods may have been periods of nearly constant or irregular eruptive activity; we cannot be more specific because many lava flows have not been dated or they cannot be dated.

The oldest lava flows that we assign to the Craters of the Moon lava field flowed away from the general location of the Great Rift. This relationship suggests that the Great Rift was a locus of source vents for even the earliest flows of the Craters of the Moon lava field, and that these early flows are covered by younger flows. Thus, we recognize that our studies may treat only the later part of the history of the Craters of the Moon lava field rather than its complete history.

Figure 3 is a generalized set of diagrams prepared from more detailed geologic maps of the Craters of the Moon lava field (Kuntz and others, 1980, 1981). The figure shows the sequential development of the Craters of the Moon lava field from the oldest recognizable eruptive period (H) through the youngest eruptive period (A). Generalized contacts between individual flows and names of source vents for the flows are shown on diagrams for each individual eruptive period, but they are not repeated on diagrams for succeeding eruptive periods.

Eruptive Period H

The earliest recognized eruptive period (H) in the formation of the Craters of the Moon lava field produced pahoehoe lava flows about 15,000 years ago. These flows are now exposed near the margins of the Craters of the Moon lava field and along the Great Rift south of Crescent Butte (Figure 3H). Source vents have not been identified for these flows, but their distribution and flow directions indicate a source on the Great Rift, possibly at Echo Crater or Crescent Butte.

The flows of eruptive period H have surfaces that are more weathered than younger flows of the Craters of the Moon lava field, but the flows of eruptive period H have little or no cover of eolian sand or loess; thus we distinguish the flows of period H from still older, loess- and sand-covered, more deeply weathered flows that are probably not part of the Craters of the Moon lava field. Because the flows of eruptive period H occur as widely scattered exposures and because we have few radiocarbon ages for flows of the group, the stratigraphic order of the flows (Table 1) and their absolute age are largely speculative.

Eruptive Period G

About 12,500 years ago, eruptions took place from at least four vents along an extension of the Great Rift in the southern Pioneer Mountains, about 2 to 5 kilometers northwest of the northern boundary of Craters of the Moon National Monument near the headwaters of Lava Creek (Figures 2 and 3G). The flows from the Lava Creek vents traveled as much as 19 kilometers to the east onto the Snake River Plain. They are some of the least evolved lavas (that is, about 44 SiO_2; see Leeman and others, 1976) of any erupted along the Great Rift; thus they probably acquired their áa character because they descended steep slopes from their source vents to the plain. The complex Sunset Cone cinder cone and its associated flows were also formed during this eruptive period. Voluminous pahoehoe lava of the Sunset flows traveled as much as 20 kilometers to the northeast over the Lava Creek flows, and pahoehoe lava of the Carey flows traveled as much as 53 kilometers to the southwest. We correlate the Sunset and Carey flows with the same source vent at Sunset Cone based on similar paleomagnetic directions for the two flows.

Eruptive Period F

The Pronghorn and Bottleneck Lake pahoehoe flows along the southwestern margin of the Craters of the Moon lava field (Figure 3F) were erupted about 10,000 to 11,000 years ago. The distribution and flow directions of the Pronghorn and Bottleneck Lake flows suggest a source vent on the Great Rift south of the present site of Sheep Trail Butte. The Heifer Reservoir pahoehoe flows at the east margin of the Craters of the Moon lava field (Figure 3F) have a radiocarbon age of about 10,700 years; thus we group them with the Pronghorn and Bottleneck Lake flows. Flow directions for the Heifer Reservoir flows suggest a source vent on the Great Rift near Crescent Butte and Echo Crater.

Eruptive Period E

We believe that eruptive period E began about 7,800 years ago with the eruption of the Lava Point áa flows. The Lava Point flows are contiguous with other áa flows located near the southern boundary of Craters of the Moon National Monument, suggesting a similar age for all the áa flows. However, we believe the Lava Point áa flows are considerably older than the other áa flows, and we assign them to eruptive period E based upon a radiocarbon age of about 7,800 years. The proximal parts of the Lava Point flows are covered by younger flows, but flow directions on exposed distal parts suggest a source vent on the Great Rift northwest of Echo Crater (Figures 2 and 3E).

Grassy Cone, a complex cinder cone on the Great Rift in the northern part of the Craters of the Moon National Monument (Figure 2), formed after the eruption of the Lava Point áa flows. Pahoehoe flows from Grassy Cone traveled as much as 52 kilometers to the south and formed the Grassy Cone and Laidlaw Lake flows which, together, created the long, narrow, composite flow along the western and southwestern margins of the Craters of the Moon lava field (Figure 3E). The stratigraphic and radiocarbon data show that the Laidlaw Lake flows are slightly older than the Grassy Cone flows, that both flows formed after the Lava Point flows, and that both flows were erupted within a short time about 7,400 years ago.

Eruptive Period D

Eruptive period D is characterized by bulbous, monolith-strewn áa flows. All of the áa flows are covered by younger flows in their proximal parts, but their flow directions and paleomagnetic data suggest that all or most of them were erupted from Silent Cone (Figure 3D). Slumped walls and cone wall remnants suggest that eruptions of áa-forming lavas destroyed the north side of Silent Cone.

Eruptive Period C

Eruptions from fissures and cinder cones along a 9-kilometer-long segment of the Great Rift between Sheep Trail Butte and Echo Crater produced the Sentinel, Fissure Butte, Sheep Trail, and South Echo lava flows (Figure 3C). Paleomagnetic evidence shows that the eruption of the Sentinel flows preceded the other flows of eruptive period C by several decades or perhaps by as much as a century. These flows consist of pahoehoe near their source vents, but several flows become áa several kilometers away from their vents. Eruptive period C ended with the formation of áa flows and Big Cinder Butte, the largest cinder cone along the Great Rift (Figures 2 and 3C). The bulbous, monolith-strewn Sawtooth, Indian Wells South, and Indian Wells North áa flows were probably all erupted from the slumped and broken southern part of Big Cinder Butte.

We have been able to obtain a radiocarbon age only for the Sawtooth flows of eruptive period C, so we cannot place limits on the beginning or the end of the period. We suspect that most of the earlier group of pahoehoe-áa flows (Sentinel, Fissure Butte, Sheep Trail, and South Echo) were erupted within a short time, probably less than 100 years. The subsequent eruptions of period C about 6,000 years ago centered at Big Cinder Butte, the source vent for the Sawtooth and probably for the Indian Wells North and the Indian Wells South áa flows. The time between the eruption of the pahoehoe-áa group of flows and the áa group of flows is unknown, but we estimate it to be several hundred years or less.

Eruptive Period B

Radiocarbon data suggest that eruptive period B began about 4,500 years ago and lasted for about 1,000 years. Black Top Butte (also called Blacktail Butte), the southeasternmost cinder cone along the Great Rift in the Craters of the Moon lava field (Figure 2), formed early in eruptive period B and is probably the source vent for the Rangefire flows (Figure 3B). Fluid pahoehoe from obscure vents along the Great Rift about 10 kilometers southeast of Black Top Butte cinder cone formed the voluminous Larkspur Park and Minidoka flows (Figure 3B) about 3,600 years ago. A small driblet spire and a few small depressions now mark the site of a formerly larger vent complex for the Larkspur Park-Minidoka flows. The vent complex was inundated by lava flows; thus its size and shape are unknown.

A broad lava cone at Devils Cauldron (Figure 3B) is indented by two steep-sided vents that formerly contained lava lakes. The lava cone is the source area for the Devils Cauldron pahoehoe flows (Figure 3B) that are stratigraphically younger than the Minidoka flows. Eruptive fissures paralleled by spatter ramparts and thin blankets of tephra extend as much as 9 kilometers northwest and southeast of Black Top Butte cinder cone (Figure 3B). The fissures are the source vents for the Deadhorse and Vermillion Chasm shelly pahoehoe flows (Figure 3B). These flows appear dusty brown, altered, and anomalously old due to weathering of their thin, highly vesicular crusts.

Eruptive Period A

We do not have radiocarbon ages on critical flows that formed during eruptive period A, such as the Highway, Devils Orchard, Serrate, Big Craters, and North Craters flows, but the stratigraphic order for flows of eruptive period A (Table 1) is reasonably well known from field relations. The absolute age of the Highway-Devils Orchard-Serrate group of áa and block lava flows is unknown, but we assume that the group formed no more than a few hundred years before the next youngest flows (Big Craters) erupted from the northern part of the Great Rift. We therefore include the Highway-Devils Orchard-Serrate group of flows as part of eruptive period A. Paleomagnetic intensity measurements suggest that the Highway flow was erupted during a peak of geomagnetic field intensity about 2,300 years ago. We cannot, however, discount the possibility that the áa-block lava group of flows is considerably older, possibly as much as several hundred or several thousand years, and represents a separate eruptive period unrelated to the eruption of the younger group of dominantly pahoehoe flows.

The sequence of events that led to the eruption of the Highway-Devils Orchard-Serrate flows is extremely difficult to decipher in the field. At present, we still disagree among ourselves about the sequence of events even after many days of careful field work. We present here two possible sequences of events for the formation of the Highway-Devils Orchard-Serrate group of flows. Additional field studies may help us to choose among and refine some of the ideas presented here.

In the first sequence of events, we suggest that eruptive period A began about 2,300 years ago with eruptions in North Crater (Figure 2) that produced a large, viscous, block lava flow (Highway) which flowed northward down the flanks of North Crater into the valley between Sunset Cone and Grassy Cone cinder cones (Figures 2 and 3A). The eruptions destroyed a large part of the north flank of North Crater and possibly other cinder cones that may have been located to the north and northeast of North Crater. The eruption of the block lava of the Highway flow was accompanied by a collapse of the north side of North Crater, during which the "highway fault" (Figure 2) formed. The "highway fault" is an arcuate, steep scarp, 1 to 10 meters high, that appears to be a segment of a ring fracture that may record the collapse of the north flank of North Crater during the eruption of the Highway flow. The Highway flow reversed its direction of flow back toward North Crater after the "highway fault" formed and after the north flank of North Crater was destroyed. Continuation of the eruption produced additional áa and block lavas that formed the Devils Orchard and Serrate flows that moved to the north and east of North Crater (Figure 3A). The Devils Orchard and Serrate flows are strewn with monoliths that were carried away from the slumped and broken northern flank of North Crater. The Highway, Devils Orchard, and Serrate flows are not in mutual contact and their proximal parts are covered by younger flows (Figure 3A), thus it is not possible to determine the age relations among them or even to determine their source vent or vents unequivocally. However, we feel that (1) the three flows may represent the eruption of successively less evolved lavas, (2) that the eruption of the highly evolved Highway flow (about 63 percent SiO_2) was so violent that it destroyed much of North Crater, and (3) that the subsequent Devils Orchard (about 61 percent SiO_2) and Serrate (about 58 percent SiO_2) lavas were viscous enough to transport large blocks of broken crater walls of North Crater for distances of several kilometers.

In the second sequence of events, we suggest that the Highway flow formed as a steep-sided tholoid in the area between Grassy Cone and Sunset Cone cinder cones (Figures 2 and 3A). Evidence for a vent beneath the northern part of the Highway flow is weak, but the viscous lava of the Highway flow may well have built up over the vent and obscured it. The southern edge of the tholoid overtopped a low ridge, and part of the viscous lava flowed to the south toward the site of North Crater. The eruption then moved southward along a fissure system and centered at North Crater (Figure 2). Viscous lava erupted from North Crater and began to destroy its northern flank and formed the Devils Orchard flow. Continued eruption of viscous lava and concomitant collapse of the north flank of North Crater formed the monolith-strewn Serrate flows (Figure 3A).

After the eruption of the Highway, Devils Orchard, and Serrate flows, about 2,250 years ago, basaltic lava erupted from two fissure systems on the southern part of the Great Rift and formed the Kings Bowl and Wapi lava fields (Figure 3A). The youngest eruptions in the Craters of the Moon lava field occurred about 2,100 years ago. These eruptions were mainly from fissures and cinder cones at Big Craters in the northern part of the Great Rift in the area between Inferno Cone and North Crater (Figures 2 and 3A). The lava from the Big Craters vents is of the pahoehoe type and has a characteristic greenish brown glassy crust. Eruptive fissures in the Trench Mortar Flat area between Big Cinder Butte and The Watchman cinder cones (Figures 2 and 3A) formed flanking spatter ramparts and thin flows of gas-charged shelly pahoehoe. Voluminous eruptions of pahoehoe lava with iridescent blue glassy crusts (Blue Dragon flows) then occurred from fissures and lava domes located south of Big Craters (Figures 2 and 3A). Most of the lava erupted from this locality flowed to the east through a series of large lava tubes. Much of the lava in the distal parts of the Blue Dragon flows was erupted from rootless vents along the lava tubes. The youngest eruptions in the Craters of the Moon lava field occurred from obscure vents on the east side of Broken Top cinder cone (Figures 2 and 3A).

SUMMARY

This paper is a general summary of our investigations of the late Pleistocene-Holocene history of the Great Rift area of the Snake River Plain. Our paleomagnetic, radiocarbon, petrographic, and geochemical studies are still in progress and will be left for later reports.

Our regional studies show that the Great Rift area is unique in the Snake River Plain. We know of only one other area, the Spencer-High Point volcanic rift zone in the northeastern part of the plain, where lava flows have been erupted repeatedly on a short segment of a fissure system in a relatively short time. In contrast, the eruptions of lava that formed the Kings Bowl and Wapi lava fields represent simple eruptive bursts of short duration that appear to be typical of most eruptions on the Snake River Plain. Why one volcanic rift zone has experienced a more complex, short-term volcanic history and why other volcanic rift zones appear to have experienced a more simple, yet prolonged volcanic history are problems that have no obvious answers at present. Factors such as regional stress buildup and release, mechanisms of magma formation and migration to the surface, and regional tectonic models that relate to volcanism are yet to be formulated into a comprehensive model for the central and eastern Snake River Plain.

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